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ABSTRACT – The Brushless Doubly-Fed Reluctance Machine (BDFRM) is being considered as a viable generator alternative to be used in wind turbines. A literature review shows that there is still a lack of researches to define a design procedure to make this machine widely used in such application. This paper aims to address this issue by considering a new BDFRM design method using a reluctance network approach and the concepts of sizing and optimization models. It also presents a case study using the proposed methodology where the torque has increased significantly whereas the iron mass has been kept to a minimum.

KEYWORDS – Design methodology, Brushless machines, Finite element methods, Electromagnetic analysis, Wind energy.

1 Introduction

The Brushless Doubly Fed Reluctance Machine (BDFRM) is being particularly considered as a viable alternative to the Doubly Fed Induction Machine (DFIG) in variable speed wind energy conversion systems (WECS). It keeps the cost advantages of the DFIG by allowing the use of a converter power rating of around 30% of the generator capacity. Additionally, the BDFRM has the advantage of maintenance-free brushless operation [1]. As evidenced in literature, although a promising solution, there is still a demand for new researches on the electromagnetic design so that this machine could be used in industrial scale. Most papers analyze existent machine designs rather than focusing on the development of new ones [2]. Similar conclusions are inferred in [3], where it is pointed out a series of fundamental issues and challenges with respects to the BDFRM design and control such as requirements to maximize the torque and power density. It is also stressed the need for a systematic design procedures to obtain optimal designs considering different sizes, power ratings and applications to meet a specific market demand. In this sense, it is proposed a new structured method on the modeling, design and optimization of the BDFRM. The main goal is to provide means to the designer to take pertinent decisions in all development phases based on fast to obtain and sufficiently accurate information, which will lead to an application specific optimal design.

2 Methodology

In general, the idea behind modeling a device has two main goals that are not necessarily satisfied simultaneously : (i) formulate the specification, i.e. to define system parameters (inputs, outputs) and constraints and (ii) solve the problem by calculating parameters with enough precision, e.g. using the Finite Element Analysis (FEA). The objective (i) aims to help the specialist to understand and define the problem. Several parameters are unknown and many combinations among them may, *a priori*, match the preliminary specification. At this stage, FEA may be useful to help in the comprehension of the device electromagnetic behavior. However, to refine the model and find an optimal solution, the use of this technique may cause delays in the development process due to large computational times and large search space. During this phase, it is usually more important to provide faster answers with a macroscopic model rather than obtaining high precision

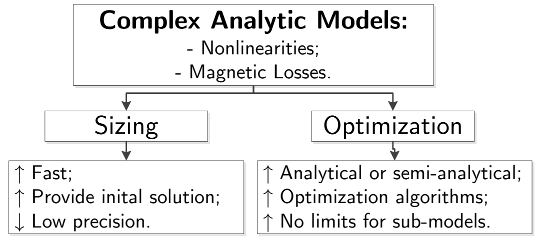


FIGURE 1 – Sizing and Optimization models characteristics.

results. Finally, the goal (ii) searches to verify if the defined parameters will satisfy the specifications and accurate results are essentials for it.

A complex model, such as one of an electrical machine, may involve several different parameters and phenomenons like iron saturation and losses, thermal constraints, harmonics, definition of slots and turns number and many others. Consequently, to assemble all constraints in a single thorough model is usually impracticable considering that many of the parameters are unknown or undefined when the design process starts. To address this issue it is proposed in the present work a methodology which uses the concepts of sizing (SM), optimization (OM) and validation (VM) models [4]. Fig. 1 illustrates the idea with two different models approaches.

The SM aims to estimate device parameters from few specifications known by the designer, typically three or four. It is clear that the SM relies on designer expertise because several parameters shall be calculated from few specifications. Some of them are estimated by knowledge and experience and the outputs calculated as a function of this assumptions. This might result in imprecisions, but the main goal of a SM is to provide a good overview of the problem. It allows to test parameters variations very quickly, which helps to restrict the search space for the optimization problem. Ultimately, this approach shall provide at least one realizable machine, that will be the starting point to the optimization model.

The OM, on the other hand, is a direct model where the specification contents (which often includes performance parameters such as voltages, power *etc.*) are not necessarily considered as inputs. Its goal is to solve an objective function with constrained input and output parameters. The limited search space may be obtained from the SM results or defined by the designer expertise. Moreover, it allows the integration of, *a priori*, an unlimited number of sub-models to describe other phenomenons like losses, thermal and application-specific constraints. The great difficulty behind the OM is that some specification requirements are usually outputs. Thus, to solve this model, the OM shall be coupled to an optimization algorithm.

The VM takes place after the SM and OM definitions. It is related to the objective (ii) and it is used to verify if the former models provided coherent and accurate results. The VM model is most often a fine and accurate model, e.g. a FEA model. After that, the next step in the development process would be to build a prototype.

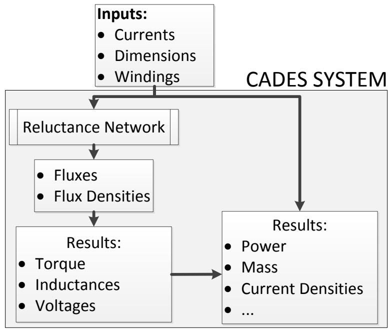
3 Building the models

Usually, the BDFRM sizing model relies on the classical electrical machine theory. In [2], for example, it is shown an interesting procedure considering analytical approaches to design a BDFRM with an ideal ducted rotor. They provide a set of design equations and an analysis of the rotor and stator windings poles combination. It is an approach that could be used on the SM definition. This paper focuses in the OM development rather than describes the SM in details. As the SM is not presented, the initial machine main dimensions, the starting point in the optimization, will be based on one machine referenced in the literature [5].

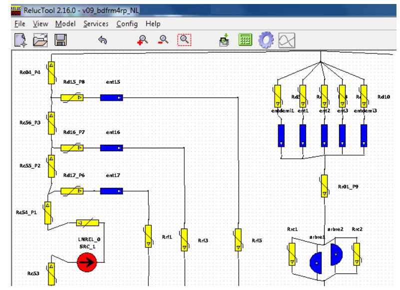
In this work it is proposed the utilization of the Reluctance Network approach to build the OM. The RN technique is very interesting because it allows a good compromise between precision and computational time. Furthermore, it may help in the comprehension of the machine electromagnetic behavior and it also allows the integration of ferromagnetic non-linearities with analytical models. The great advantage of this method, however, is that it permits the use of gradient based optimization algorithms, which gives fast an accurate results for a wide operating points range.

The optimization model is shown in the diagram represented in Fig. 2a. The input parameters are defined considering the initial machine. The RN (Fig. 2b) is build as a function of the machine dimensions to calculate the reluctances in each part where the flux lines are significants. The models are developed by using the software package Cades/RelucTool.

The RN is used to calculate the fluxes and flux densities around the machine considering ferromagnetic non-linearities. These quantities are used to calculate performance parameters such as torque, voltages and self and mutual inductances. Several others equations may be included directly in the Cades system to describe different aspects in the machine such as



(a) Optimization model implemented in CADES.



(b) One quarter of the implemented BDFRM Reluctance Network model.

FIGURE 2 – Optimization Model and the reluctance network.

power, total mass, current densities and so on. The equation system is then compiled and coupled to the SQP optimization algorithm for system solution.

4 Case Study

4.1 Machine Modeling

The BDFRM stator is constructively similar to the induction machine, but it has two sets of three phase windings with different number of poles. Magnetic coupling between the two stator windings is achieved using a reluctance rotor with number of poles equal to the total number of pole pairs on the stator. The rotor can be salient, axially laminated or radially laminated with flux barriers (ducted) [1, 3]. The reader is referred to [6, 3] and their references to find a complete review on the machine analytical modeling.

Since the main goal of the case study is to illustrate method capabilities rather than propose a ready to fabricate machine, the salient pole rotor has been chosen due to its simpler analytical modeling. Similar approach with minor modifications could be used for different rotor types. It has been chosen a combination of $p_r = 4$ rotor poles and $p = 1$ and $q = 3$ pole pairs in the primary and secondary windings, respectively. Fig. 2b shows a quarter of the RN implemented as part of the OM. To develop this network, a first FEA has been performed in the machine considering a DC excitation only in phase A of the primary winding (i_{1A}). This procedure allows to define the most significant flux paths where the reluctances should be located in the network and also to calculate λ_{1AA}, the phase A flux linkage, to verify the initial RN model accuracy. The machine torque is calculated using the following steady state analytical equation [6] :

$$T_e = \frac{3}{2}(p+q)L_{12}I_1I_2\sin(\gamma+\alpha) \tag{1}$$

where L_{12} is the mutual inductance between the two sets of three phase windings, I_1 and I_2 are the peak current values in the primary and secondary windings, respectively, γ is related to the rotor initial position and α is the phase difference between the currents in the primary and secondary windings.

Based on the salient pole analytical model [6] and in order to simplify the RN construction, some idealized assumptions have been considered to find a simplified torque expression. This parameter can be shown to be proportional to :

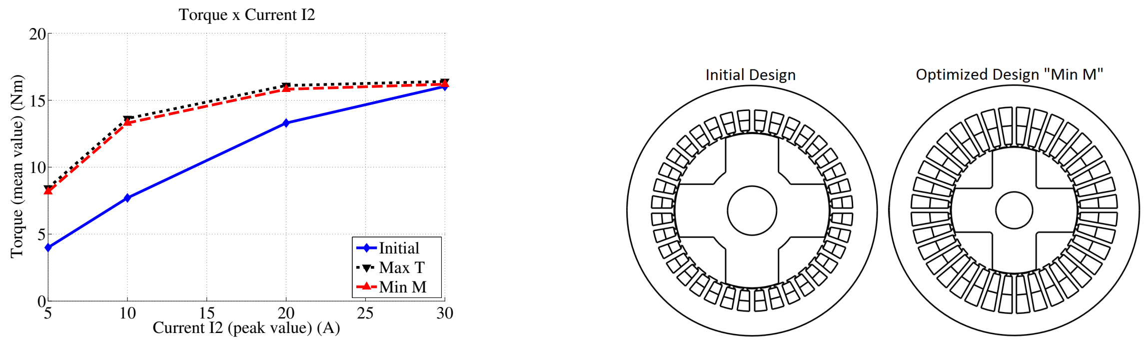
$$T_e \propto \frac{n_2}{n_1}\frac{\lambda_{1AA}}{i_{1A}} \tag{2}$$

where n_1 and n_2 are the total number of turns per phase per pole pair divide by 2 in the primary and secondary respectively.

4.2 Numerical Analysis

To verify the methodology, two optimization analysis have been performed using CADES at the operating point $I_1 = I_2 = 7.5\ A$: "*Max T*" aims to maximize the torque and "*Min M*" to minimize the mass while keeping the mean torque maximum found in "*Max T*". In both calculations the input physical parameters have been constrained in specific ranges, but left free to vary within the range. The minimum air gap length constraint has been set to the value considered in the initial machine. The external diameter and the stack length have been kept constant to match a specific machine frame. The thermal constraints are indirectly taken into account by limiting the current density in the windings at $5\ A/mm^2$.

At this point, the validation model (VM) based on FEA takes place in order to verify the optimization output parameters. It is important to notice that the FEA in this strategy is also very important, because the optimization results are



(a) (b)

FIGURE 3 – Torque results and the cross sectional view of initial and optimized desings.

verified using it. The advantage of the aforementioned procedure is to reduce the number of FEA calculations (so saving time) to obtain an optimized design. The resulting machines are verified using multi-static non linear FEA for different levels of current I_2. The current $I_1 = 5\ A$ and angular mechanical speed $\omega_{rm} = 750\ rpm$ are kept constants. The VM results are summarized in Table 1.

TABLE 1 – Torque and mass comparison between designs.

Torque [Nm]	$T_{Initial}$	T_{MaxT}	*Dif %*	T_{MinM}	*Dif %*
$T_{I2=05A}$	4.0	8.4	111.3 %	8.2	104.5 %
$T_{I2=10A}$	7.7	13.6	77.0 %	13.3	72.6 %
$T_{I2=20A}$	13.3	16.1	21.1 %	15.8	19.0 %
$T_{I2=30A}$	16.0	16.4	2.3 %	16.2	1.0 %
Mass [kg]	51.7	42.0	-18.8 %	41.6	-19.5 %

The estimated iron mass calculated analytically has decreased approximately 20 $\%$ compared to the initial design. The mean torque curves of the optimized machines "*Max T*" and "*Min M*" are shown in Fig. 3a. It can be seen that the torque has significantly increased in all operating range. The different designs can be seen in Fig. 3b.

Although the fact that the OM has given indeed good results for the optimized design, it is worth to mention that the RN used in the case study as example is oversimplified. This may eventually result in low accuracies in the determination of some performance parameters when compared to FEA depending on the operating point. Further work shall be made to increase its robustness. Nevertheless, it does satisfies its objective by showing an "appropriated direction" in order to build an optimized design. The provided example which maximizes the torque whereas keeping the mass to a minimum illustrates the interesting possibilities on using this procedure.

References

[1] D. G. Dorrell, A. M. Knight, and R. E. Betz, "Improvements in Brushless Doubly Fed Reluctance Generators Using High-Flux-Density Steels and Selection of the Correct Pole Numbers," *IEEE Transactions on Magnetics*, vol. 47, pp. 4092–4095, Oct. 2011.

[2] A. M. Knight, R. E. Betz, and D. G. Dorrell, "Design and Analysis of Brushless Doubly Fed Reluctance Machines," *IEEE Transactions on Industry Applications*, vol. 49, pp. 50–58, Jan. 2013.

[3] L. Xu, B. Guan, H. Liu, L. Gao, and K. Tsai, "Design and control of a high-efficiency Doubly-Fed Brushless machine for wind power generator application," in *2010 IEEE Energy Conversion Congress and Exposition*, pp. 2409–2416, IEEE, Sept. 2010.

[4] R. Carlson and F. Wurtz, "The concepts of sizing and optimization model : Applied to the optimal design of a Permanent Magnet Generator," in *International Aegean Conference on Electrical Machines and Power Electronics and Electromotion, Joint Conference*, (Istanbul, Turkey), pp. 651–656, IEEE, Sept. 2011.

[5] I. Scian, D. Dorrell, and P. Holik, "Assessment of Losses in a Brushless Doubly-Fed Reluctance Machine," *IEEE Transactions on Magnetics*, vol. 42, pp. 3425–3427, Oct. 2006.

[6] R. E. Betz and M. G. Jovanovic, "Introduction to the Space Vector Modeling of the Brushless Doubly Fed Reluctance Machine," *Electric Power Components and Systems*, vol. 31, pp. 729–755, Aug. 2003.